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This research investigates how the human auditory system processes temporal properties of a complex signal across two or more regions of the frequency spectrum. Much of the primary research from the original proposal on envelope phase disparity using AM carriers is complete. Several findings are outlined. A computer model has also been developed and analyzed to consider issues of cross-spectral temporal disparities. The model is based on the auditory-nerve point-process model which has been successfully applied to binaural localization by Colburn, among others.

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Time-frequency Factors in Auditory Perception

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by

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Table of Contents

1 Scientific goals

This research investigates how the human auditory system processes temporal properties of a complex signal across two or more regions of the frequency spectrum. We currently use psychophysical procedures to evaluate auditory sensitivity to disparities in the relative timing of spectral events for a special class of acoustic signals and techniques from signal detection theory to incorporate neurophysiological results into models that account for such sensitivity. The signals under investigation are amplitude-modulated or frequency-modulated sinusoidal carriers in which the modulators differ only with respect to a phase disparity. By studying these signals, we intend to model auditory processes which are responsible for comodulation masking release, coherence perception, and object perception.

2 Description of studies

2.1 Envelope Phase Discrimination for SAM carriers: Experiments

Experimental Results. Much of the primary research from the original proposal on envelope phase disparity using AM carriers is complete. We have shown that

1. When normalized to the phase of the amplitude modulator, thresholds are relatively constant for modulation frequencies up to 64 Hz. Above 64 Hz, the data suggest that there are at least two populations of subjects, those whose sensitivity drops considerably such that they perform at chance for modulators of 128 Hz and beyond, and those whose sensitivity improves.

2. Carrier separation appears to have little effect on performance for carriers separated more than one octave.

3. Phase disparity thresholds are directly proportional to the depth of amplitude modulation. For modulation depths less than -18 dB, subjects perform at chance, despite the fact that the amplitude modulation at -18 dB lies 5-7 dB above detection thresholds for AM and is clearly detected by subjects at both carriers.

4. In-phase amplitude modulation does not appear to be a special case of time-frequency analysis in the auditory system, as might otherwise be expected if cross-spectral coherence were an important attribute of auditory signals. Envelope phase discrimination functions obtained for a variable phase disparity between the envelopes of the standard stimulus are convex with the phase increment of the comparison stimulus and achieves a minimum in the neighborhood of 90 degrees.

5. The relative phases among components in a harmonically-rich envelope do not appear to contribute to the detection of phase disparities across regions of the spectrum.

The five conclusions above are based on research completed during the first two years of the study. In addition to these major points, we have pursued the dependence of phase sensitivity on modulation depth in detail over the past year. We have measured phase disparity thresholds for a variety of signal envelopes and have established a correspondence between these thresholds and the rms energy (or power) of the envelopes. This correspondence allows us to predict phase disparity thresholds for a variety of stimulus complexes from the phase-disparity/energy curve for a pair of SAM carriers.

2.2 Envelope Phase Discrimination for SAM carriers: Modelling

We have developed and analyzed the performance of a model for cross-spectral temporal disparities. This model is based on the auditory-nerve point-process model which has been successfully applied to binaural localization by Colburn, among others. Discharge activity in the VIIIth nerve is represented as a non-homogeneous Poisson process. Under the assumption that different sets of fibers are driven by each of the carriers, we can derive the form of the maximum likelihood receiver for the task of discriminating envelope phase disparity. This receiver can be summarized as a point-process implementation of a cross-correlator.

The auditory-nerve model has been applied to the problem of detecting a change in phase disparity between envelopes at two different carrier frequencies. The model has been implemented on a computer and the performance of an ideal receiver has been evaluated through simulations.

Two parameters of the model are important: the duration and shape of the cross-correlator window, e.g., the temporal weighting of the period over which the occurrence of spikes from the two time-series are determined to coincide. Assuming a rectangular window, the duration was varied to yield psychometric functions that agreed with those obtained for human observers. These durations were on the order of 5 ms and provided excellent agreement with the human results. Alternatively, performance can be summarized by the change in cross-correlation $\Delta\rho$ necessary to discriminate among envelopes. These values ranged from .22 to .51 for the three subjects in our studies.

2.3 Envelope Phase Discrimination for SFM carriers

We have begun the proposed experiments on cross-spectral temporal disparities using FM carriers. The general goal of these experiments is similar to that of the AM carriers; we are interested in the extent to which variations in the temporal structure of a short-term power spectrum across frequency are preserved in the auditory system. A straightforward approach to relating this problem to our research on AM carriers is to hypothesize that the auditory system demodulates the FM signal and performs the cross-spectral temporal disparity on the basis of a cross-spectral envelope disparity for two frequency channels.

Our basic results thus far show that sensitivity to a disparity in the phase of the FM modulator is monotonically related to the frequency excursion ΔF of the FM signal, where the general form for FM modulation is

$$s(t) = \sin(2\pi f_c t + \beta\cos(2\pi f_m t + \phi))$$

and $\Delta F = \beta f_m$. This relationship, however, exhibits a strong threshold characteristic as shown in Figure 1 in which phase disparity thresholds are shown for 4 different modulation frequencies with carrier frequencies at 500 and 2000 Hz. When $\Delta F < 64$ Hz, performance deteriorates rapidly so that subjects are unable to discriminate between an in-phase and 180° out-of-phase condition. Above 64 Hz, performance depends weakly on frequency excursion. There appears to be a slight non-monotonic dependence on modulation frequency as well.

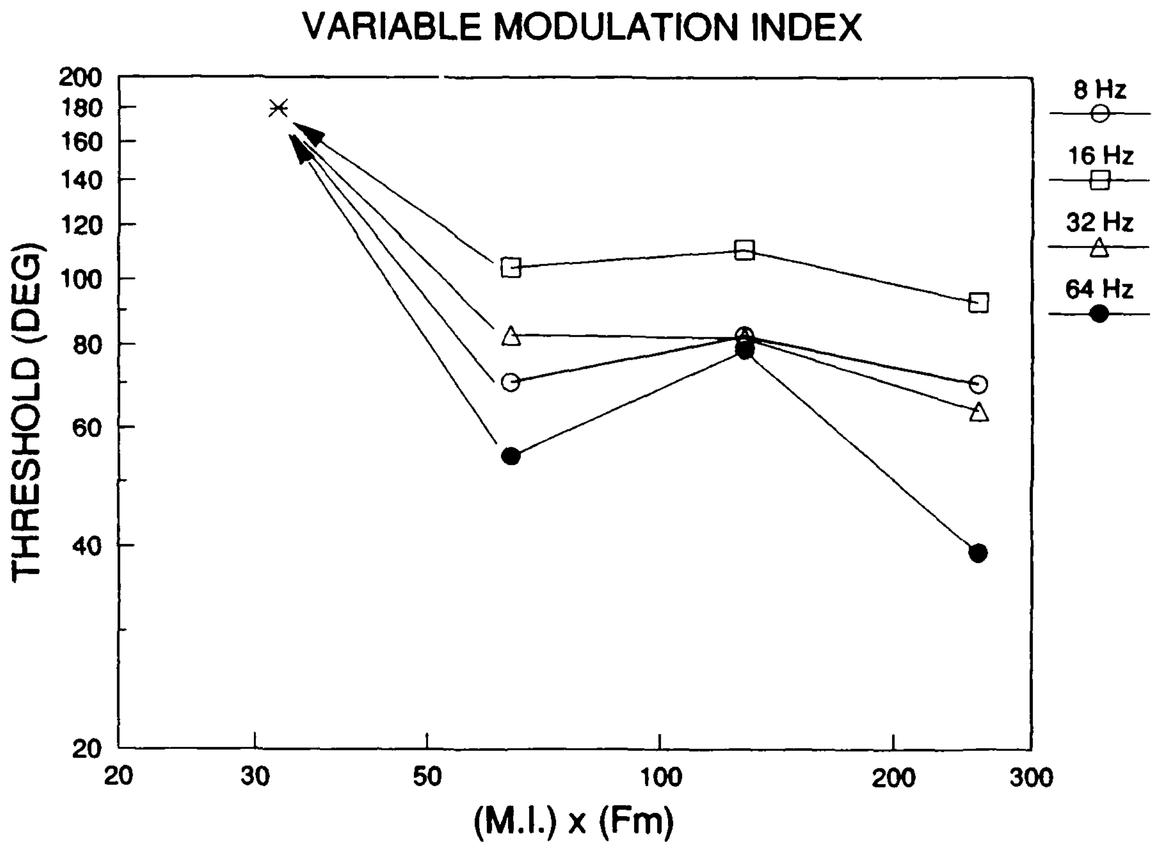

Figure 1. Effects of ΔF (= $M.I.xFm$) on phase disparity threshold for a two-carrier FM complex. Carrier frequencies are 500 and 2000 Hz.

Varying the relative phase offset of the standard appears to have the same effect on the phase disparity threshold as was observed for AM stimuli. Figure 2 shows results for S1 for standard offsets ranging from 0° to 180° in which modulation frequency ranged from 8 to 64 Hz. Modulation index was varied, for each modulator, so that ΔF remained constant at 128 Hz. Though the general trend of these data is the same as that for AM, the overall displacement of these curves to higher disparity thresholds is consistent with observations made throughout our studies of FM carriers: sensitivity is consistently poorer than is observed in the AM conditions.

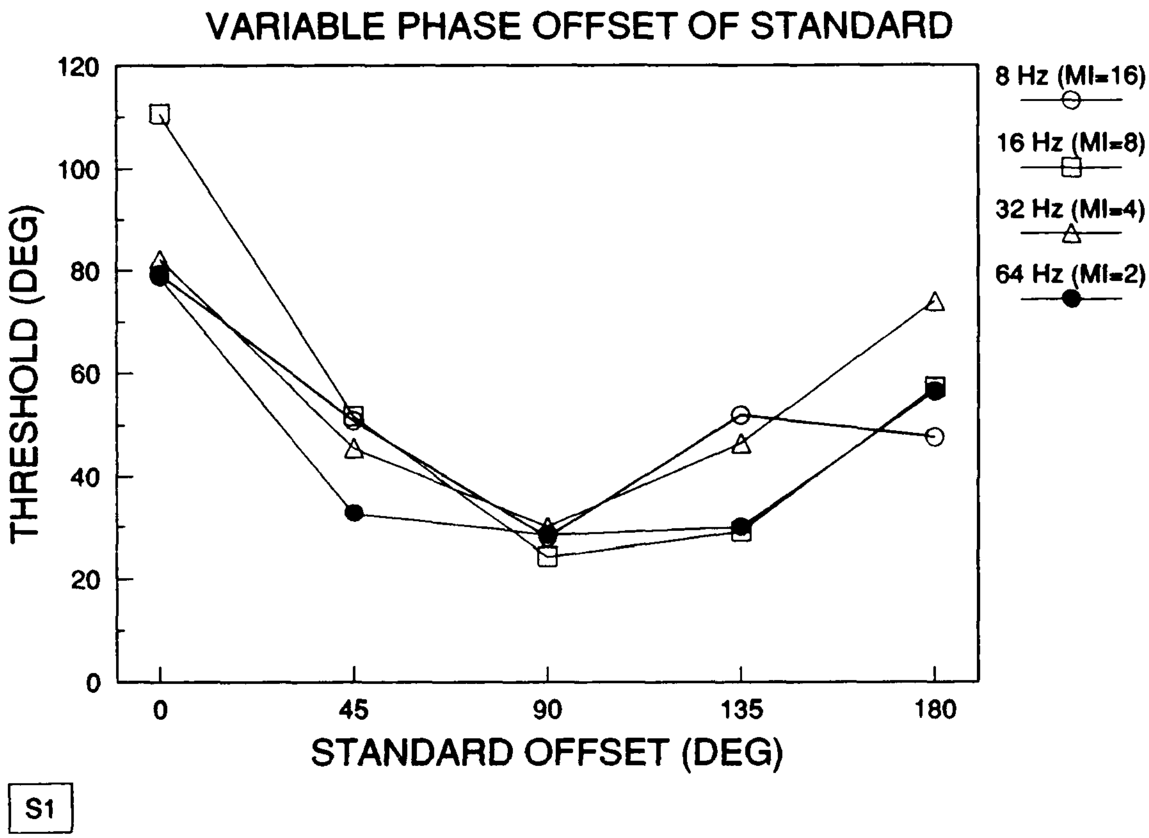

Figure 2. Effects of the relative phase offset of the standard on phase disparity threshold for a two-carrier FM complex. Carrier frequencies are 500 and 2000 Hz.

To place this latter conjecture on more quantitative grounds, the Roex auditory filter model was used to extract the amplitude envelope for a carrier at 500 Hz and one at 2000 Hz. Phase disparity thresholds for these AM-equivalent signals lay considerably below those measured for the original FM signals; it was necessary to widen the bandwidths of the auditory filters by more than a factor of 4 to account for the FM thresholds through an "AM-equivalent" model of FM demodulation in the auditory system.

We have observed other anomalies between the FM and AM results; asymmetries are observed with respect to frequency excursions at different carriers and there is a strong effect of carrier frequency on threshold. Both of these results cannot be readily accounted for using standard auditory filter bandwidths and a straightforward approach to FM demodulation at the auditory periphery. In general, the evidence indicates that there is sufficiently rich information preserved at the level of the auditory filter to support much lower disparity thresholds in these tasks.

2.4 Adaptive psychophysical procedures

Our measurements of cross-spectral envelope disparities for AM signals were based on data obtained using Levitt's 2IFC tracking procedure as a rapid means of assessing the 70.7% point of the psychometric function. Our choice of stepsize was governed by the psychometric functions measured for the case in which the standard had a zero-degree phase disparity. The question of whether the same stepsize should be used for the phase discrimination task led us to consider the issue of sensitivity of the threshold estimate to the shape of the psychometric function. Levitt's analysis of this problem is particularly weak and we decided to pursue a mathematical treatment of the up-down method which could at least produce a better set of tools for assessing issues of sensitivity, number of reversals as a stopping criterion, and the statistic selected to summarize the data.

Our results were presented at the 1988 Spring meeting of the Acoustical Society of America and have since been submitted for publication. We have shown that Levitt's procedure can be summarized as a random walk generated by a Markov chain. Using this Markov formulation, we have proven several useful properties of Levitt's method including that the probability of occupying a given level approaches a unimodal distribution, the mode of which corresponds to Levitt's "equilibrium" point (which is based on conditional arguments). We have also shown that Levitt's procedure can yield biased estimates of performance and that this bias increases with decreasing number of reversals and larger step sizes. As an example, a 4-dB step size for measuring the threshold of a pure tone signal in a wideband noise estimates the 65% point (rather than 70.7%) of the psychometric function given a stopping criterion of 12 reversals. This analysis was performed in conjunction with an NIH-funded research project in which we are collecting data on patients with auditory prostheses and for which rapid estimators are truly needed.

3 Conferences and publications

3.1 Manuscripts submitted for publications

The titles of three papers submitted for publication during the past year are shown below and copies of these submissions are provided in the Appendix.

Wakefield, G. H. and Edwards, B. W. (1988). "Detection and discrimination of cross-spectral envelope phase disparity," *J. Acoust. Soc. Am.*, accepted for publication pending revisions.

Wakefield, G. H. and Edwards, B. W. (1988). "Markov analysis of transformed up-down methods in psychophysics: I. Asymptotic properties," *J. Acoust. Soc. Am.*, accepted for publication pending revisions.

Wakefield, G. H. and Edwards, B. W. (1988). "Markov analysis of transformed up-down methods in psychophysics: II. Small-sample properties," *J. Acoust. Soc. Am.*, accepted for publication pending revisions.

All three papers were submitted to the Journal of the Acoustical Society of America and each has been accepted for publication, pending revision. In the case of the two papers on adaptive psychophysical procedures, the reviewers requested a major re-organization of the material into a "theoretical" paper, containing theorems and proofs, and a "practitioner's" paper with a discussion of the implications of the theoretical results to psychophysical research.

3.2 Conferences

Edwards, B. W. and Wakefield, G. H. (1988). "Small sample statistical analysis of Levitt's adaptive psychophysical procedure," *J. Acoust. Soc. Am.*, 83, S1(17).

Edwards, B. W. and Wakefield, G. H. (1989). "The effect of envelope energy on the discrimination of cross-spectral envelope phase disparity," to be presented at the 1988 Spring meeting of the Acoustical Society of America.

Wakefield, G. H. and Edwards, B. W. (1989). "Cross-spectral envelope phase discrimination for FM signals," to be presented at the 1988 Spring meeting of the Acoustical Society of America.

Wakefield, G. H. and Edwards, B. W. (1989). "Cross-spectral envelope processing in the auditory system," Special Session on the Perception of Complex Sounds, 1989 meeting of the Midwest Psychological Association, May, 1989, Chicago, Illinois.

4 Specific aims for the coming year

During the coming year, we will investigate further the appropriate variable for quantifying the dependence between temporal disparity thresholds and envelope "excitation". Our evidence clearly points to the second moment of the envelope as important, but does not clearly indicate whether "energy" or "power" is the appropriate normalizing factor. We will directly test this distinction by manipulating envelope energy by varying the duration of the signals. Our evidence also indicates that auditory sensitivity to temporal disparities for a variety of envelopes can be predicted from measures obtained for sinusoidal envelopes; however, we intend to determine the limits to which this generalization is true. In particular, we will investigate two limiting cases, pulsatile signal complexes and narrowband noise signal complexes, with respect to this simple empirical model.

We will investigate modifications of the auditory-nerve model to account for the dependence of sensitivity on envelope energy. These investigations will rely heavily on information gained from computer simulations of decision algorithms based on neural point processes. In order to effectively pursue this research, considerably greater computational power will be necessary than is currently available in our laboratory. A request is forthcoming concerning this issue.

We will continue our investigation of phase sensitivity for frequency modulation and will, in particular, focus on the issue of how FM is represented in the auditory system. Our approach will be to collect further evidence concerning FM sensitivity in parallel with hypothetical "AM-equivalent" experiments. It appears that our problems are shared by other researchers who have investigated FM over the past fifty years - many of the "rules" anticipated on the basis of simple AM-equivalent models appear to be violated for FM tasks. However, we believe that our psychophysical task, since it is formulated with respect to suprathreshold AM and FM stimuli, may lead to clearer tests of various theories for representing frequency modulation in the auditory system.

5 Appendix: Copies of manuscripts submitted for publication

Wakefield, G. H. and Edwards, B. W. (1988). "Detection and discrimination of cross-spectral envelope phase disparity," *J. Acoust. Soc. Am.*, accepted for publication pending revisions.

Wakefield, G. H. and Edwards, B. W. (1988). "Markov analysis of transformed up-down methods in psychophysics: I. Asymptotic properties," *J. Acoust. Soc. Am.*, accepted for publication pending revisions.

Wakefield, G. H. and Edwards, B. W. (1988). "Markov analysis of transformed up-down methods in psychophysics: II. Small-sample properties," *J. Acoust. Soc. Am.*, accepted for publication pending revisions.